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CIGAR ULTRASONIC INSPECTION OF CRNL/CANDEV PRESSURE TUBE DB3 CONTAINING INTENTIONAL DEFECTS

Report No. 88-27-K

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ABSTRACT

A CANDEV-funded pressure tube containing about 50 deliberately implanted defects was scanned using CIGAR-type ultrasonics and new CIGAR software. In comparison with the new manufacturing inspection procedure performed at Bristol Aerospace Ltd. (BAL), CIGAR detected four or five more defects and proved to be at least twice as sensitive. Three defects were not detected by either CIGAR or BAL, and CIGAR was unable to scan four (mostly large) defects. Otherwise, the in-service (CIGAR) and new manufacturing inspections (BAL) were similar.

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83-207-451	826.14	March 4, 1988	88-27- K

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EXECUTIVE SUMMARY

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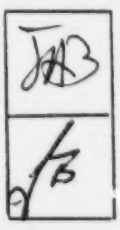
CANDEV have funded a project at CRNL (Chalk River Nuclear Laboratories) to evaluate the defect detection capabilities of pre-service (manufacturing) inspections. This project requires the manufacture of pressure tubes with deliberately implanted defects of various depths, lengths and orientations. Tube DB3 is the third such tube, and contains about 50 axially-oriented defects. DB3 was initially inspected by CRNL using the old manufacturing inspection procedure, then by Bristol Aerospace using a recently developed (new manufacturing inspection) procedure and equipment. This report describes inspection of tube DB3 using CIGAR (Channel Inspection and Gauging Apparatus for Reactors) in-service inspection equipment and procedures in the laboratory.

CIGAR was unable to scan four (mostly large) defects due to physical constraints. In comparison with the new manufacturing inspection procedure, the in-service inspection detected four (possibly five) more defects, and was at least twice as sensitive. The data do not allow a more accurate estimate of CIGAR's increased sensitivity. Both CIGAR and the new manufacturing inspection did not detect three defects, but otherwise gave similar results. Comparison with the old manufacturing inspection procedure will be performed by CRNL.



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To

Dr. T.J. Carter
Reactor Development and
Structural Analysis Engineer
Design and Development
H10A16

CIGAR ULTRASONIC INSPECTION OF CRNL/CANDEV PRESSURE TUBE DB3 CONTAINING INTENTIONAL DEFECTS

1.0 INTRODUCTION

1.1 Background

Pressure tubes are the primary pressure boundary for CANDU nuclear reactors, and are critical for safety and economic reasons. Pressure tube duty cycles are very severe, with temperature, stress, environmental and radiation factors. CANDU reactor pressure tubes are made of Zr-Nb , are about 6 metres in length, 103 mm in diameter and 4.2 mm wall thickness. The pressure tubes contain the natural uranium fuel bundles, cooled by heavy water.

During the history of the CANDU system, a number of pressure tube problems have arisen. Pressure tubes have elongated and sagged due to radiation creep; delayed hydride cracks have occurred in rolled joint areas in some earlier reactors; manufacturing defects have occasionally been observed (such as the Bruce 2 N06 defect); and hydride blistering has occurred due to pressure tube/calandria tube contact.

1.2 Pressure Tube Inspections

New pressure tubes undergo routine inspection before installation, and periodic in-service inspection, using gauging, ultrasonic and eddy current techniques. The pre-service or manufacturing inspection uses eddy current testing on both the inside and outside surfaces, plus ultrasonic shear wave volumetric inspection/1/. In-service inspections are performed using CIGAR (Channel Inspection and Gauging Apparatus for Reactors), which uses ultrasonic shear wave transducers for volumetric inspection.

The (old) manufacturing inspection procedure compared the ultrasonic signal amplitude from a 76 micron (3 thou.) notch with that from the defect as cause for rejection, in an ASME-type procedure. Reflectors up to 11 dB below this notch in signal amplitude are re-evaluated to determine whether they are rejectable by the 76 micron notch criterion or not.

Since the Bruce 2 N06 pressure tube failure, which initiated from a very tight manufacturing defect, a new manufacturing inspection procedure has been developed, based on CIGAR technology/2/. The new procedure uses four CIGAR 10 MHz, spot-focussed shear wave ultrasonic transducers, plus a 100 MHz highly focussed normal beam transducer. The new manufacturing inspection procedure uses the same 76 micron notch as reference standard, but scans 12 dB (a factor of 4 times more sensitive) above the threshold. Signals above the new threshold are recorded, but the tube is not directly rejected unless the signals are higher in amplitude than the 76 micron notch, ie. the old reject threshold. Thus the recording threshold is four times as sensitive as the reject threshold for the new manufacturing procedure.

CIGAR uses a somewhat different ultrasonic calibration and recording system, called "grass-level plus". CIGAR calibration involves performing a power check on the axial and circumferential probe pairs, which produces calibration signals similar in amplitude to a 76 micron outside surface notch. Then the gain is increased until the signals from the fuel bundle scratches reach 10-15% full screen height. This was typically 20-26 dB in Pickering 1 and 2 inspections/3/, which did not use remote pulser preamps. Rejection of defects by CIGAR is a more complex issue, since it requires characterizing the defect to determine its threat to structural integrity.

One other major difference between the in-service and manufacturing inspections is that in-service inspections are performed from the inside of the tubes while manufacturing inspections are performed from the outside of the pressure tube. The differences between the three inspection techniques are summarized in Table 1.

2.0 CANDEV PRESSURE TUBE DB3

CANDEV have funded an experimental program at Chalk River Nuclear Laboratories to manufacture pressure tubes with deliberately-implanted defects, and to inspect them using the old manufacturing procedures (W.P. 0732). Defects are made by putting electro-discharge machined (EDM) notches in a pre-extrusion billet, then extruding as normal. The initial EDM notch size and orientation dictate the post-extrusion defect, but typically there has been some discrepancy between theory and practice.

The first CANDEV tube was inspected by CIGAR in the fall of 1985/4/ after the CRNL inspections. The defects were large and readily detected, despite the poor finish on the tube. The second and third tubes were sent to Bristol Aerospace Ltd (BAL) in Winnipeg, Manitoba for inspection using the new manufacturing procedure after testing at CRNL using the old manufacturing procedure. The third tube, DB3, was then sent to Ontario Hydro Research Division NDE Centre for a CIGAR-type in-service inspection. This report describes the results from this CIGAR inspection, and compares these with the new manufacturing procedure results from BAL /5/. This work only investigates detection, not sizing or characterization of defects.

3.0 CIGAR EXPERIMENTAL INSPECTION PROCEDURES

Tube DB3 was mounted vertically on the new pressure tube scanning rig, and scanned using a conventional Zr-Nb CIGAR ultrasonic module and centering rollers. The tube had to be scanned in two halves, but due to its length, a 5 cm section in

the middle remained unscanned. Due to noise problems with the slip ring, the tube was scanned in a raster mode, rather than a helical pattern, though this would make a negligible difference to the results. A 3 millimetre axial step was used, as for an in-service CIGAR general helical scan. No detailed scans (1mm or less axial step) were performed. Scanning speed was 20 rpm, as for CIGAR.

Ultrasonic data was recorded using the new CIGAR high-resolution, colour graphics, which also provided the opportunity to test this software. The graphics can be displayed as C-scans or C-scan isometrics, and selected areas can be "blown-up" to give detailed images. The data is displayed in colour on a high resolution screen, and the colour spectrum can be changed at the touch of a key to highlight specific defect amplitude regions. This permits the shading in or out of specific features. A cursor feature allows precise axial, circumferential and amplitude data on any pixel. Data is printed out on a HP Paintjet colour printer. (A marker system for reflections above, say 50% FSH is also available on the display, but the yellow colour used may show poorly on the reproductions in Figures 1-11).

Ultrasonic calibration was performed as usual. Circumferential probe power check was 14 dB to 50 % FSH, and axial probe power check 12 dB. Scanning level was 34 dB on all four channels, ie 20 dB above power check on the two circumferential probes, 22 dB above power check on the axial probes. These are within the normal scanning level ranges for CIGAR(ette), being 2 dB below the Pickering 1 and 2 average. Nominal recording threshold is 50 % FSH, but more emphasis is placed on defect characterization with CIGAR than with most inspection systems, so this level is not necessarily a reject threshold.

4.0 RESULTS

4.1 C-Scan Results

Figures 1 and 2 show conventional C-scans of the two halves of the DB3 pressure tube, for the circumferential probe pair only. Many defects are visible, and these are labelled from the markings on the tube using CRNL's terminology and reference. Some of the known defects produce recordable signals on both inside and outside surface gates; for example, defect K8 on the outside surface also showed on the full-skip (inside surface), and defect N8 on the inside surface showed on both channels on the outside surface. These secondary reflections are labelled K8(S) and N8(S) respectively.

The following defects were not scanned since they were too close to the ends of the tube; K9, L9, N9 and L1. An unidentified reflector near K8 was probably not K9 as it had the wrong rotational and axial position. Defect L5 was not detected since it happened to be at the dead area (about 5 cm long) in the middle of the tube. Defects N5 and N1 were only partially scanned, but were both detected on at least one pass. The location of the defect labelled N5 was confirmed by CRNL, and comparison with the BAL results indicates that another reflector displaced axially may be part of the same defect.

Defects L4, N4 and M4 were not detected, though the defect locations were scanned. The defect tentatively identified as N2 had the wrong axial location by several cm, and was not confirmed. Defects K1-8, L2, L3, L6-8, M1-3, M5-8, N3, N5-8 were positively identified. An unexpected reflector, which could have been N4,

was observed on the inside surface near the middle of the tube. No axial scans were printed, partially because the outside surface axial noise was exceptionally high (about 50% FSH).

The configuration of the CIGAR probes is such that all four probes' beams meet at a point on the inside surface. Consequently, the circumferential probe's beams are separated by 8 mm (or degrees) on outside surface defects, which explains the double images on the half-skip (outside surface) C-scans.

4.2 Isometric Printouts

Figures 3 a-f show combined isometrics of the tube, in more typical CIGAR format. The outside surface (half-skip) scans are on the left, and the inside surface scans on the right. This is the same information provided in Figures 1 and 2, but in a different visual format. Using the isometrics, a good impression of the amplitude envelopes of the defects can be obtained, which can be important for defect characterization.

Figures 4 - 11 show detailed isometrics (more accurately, blow-ups) of the defect areas around M1/2, M3, M4, N1-N4 and L4. The M1/2 defect can be seen to be a series of low amplitude peaks, and the M3 defect to be well above recording level. Defects M4, N4 and L4 are not detectable/recordable. Defect N1 was only detected on one pass since it was at the end of the scanning range, the defect thought to be N2 was detected on two passes, and N3 on just one pass.

5.0 COMPARISON WITH BAL NEW MANUFACTURING INSPECTION PROCEDURE

The BAL (new manufacturing) inspection procedure results are shown in Figures 12 and 13. The BAL data is presented as strip chart recordings, giving axial (but not rotational) position versus signal amplitude for the inside and outside surfaces. For a tube containing as many defects as DB3, this kind of output has significant limitations compared with C-scans, but normal pressure tubes have very few defects. BAL record data if it is above 50 % FSH on the strip chart, but reject according to the old manufacturing inspection criterion (12 dB higher).For example, L7, which was just under 50% FSH, would not be recorded. Defect N7 would have been recorded by BAL since it was over 50% FSH, but would have been acceptable using the 76 micron notch criterion. Both L7 and N7 were easily detected by CIGAR.

Table 2 compares the BAL (new manufacturing inspection) results with the CIGAR (in-service) inspection of tube DB3. Defects L7, N1, N2 and M1-2 would have been recorded by CIGAR but not by the new manufacturing inspection. (BAL recorded defect M4 as detected, but it was probably defect M3 mislabelled).

Tables 3 and 4 compare the estimated signal amplitudes from the various defects using the BAL strip charts and Figure 3. In all cases, the CIGAR inspection produces higher signal amplitudes, as expected. However, it is not possible to quantify the differences in amplitude because all the CIGAR signals are greater than 100% FSH, ie. saturated. On the inside surface signals, defects N1, M1/2, N2, and M2 are 50% FSH or below on the BAL scan, while all are over 100% FSH on the CIGAR inspection (see Table 3). This indicates that CIGAR is at least twice as

sensitive on the inside surface as the new inspection procedure. Defect L7 in Table 4 is 30% FSH on the BAL inspection, and over 100% FSH in the CIGAR inspection. Unfortunately, defects L5 and L1 were not scanned by CIGAR. However, L7 suggests that CIGAR is at least three times as sensitive on the outside surface. It is probably inadvisable to compare secondary signal amplitudes (eg. M8(S)), since these may be influenced by factors such as inside/outside inspection and waterpath changes (see below).

Despite the similarities in equipment, there are a number of differences between the BAL and CIGAR scans. First, BAL increase the gain 12 dB over a 76 micron notch, while CIGAR increases 20 – 26 dB over a similar level. Thus CIGAR scans should be much more sensitive, which they are, though the difference is difficult to quantify. Second, CIGAR inspects from the inside of the tube, not the outside. In the laboratory, CIGAR has been observed to be more sensitive to outside surface defects/5/, probably due to focussing effects. In contrast, due to the requirements of the inspection procedure, BAL attempt to balance the signal amplitudes from inside and outside surface notches, which may require waterpath adjustments.

The results can be summarized by saying that, in general, the CIGAR (OHRD) and new manufacturing inspections (BAL) agreed well. The third comparison, the old manufacturing inspection versus the new manufacturing inspection and with in-service inspection, remains to be correlated by CRNL. Previous results/5,6/ suggest the new manufacturing procedure and CIGAR will prove to have significantly better detectability of defects than the old manufacturing procedure. Later, CRNL will be sectioning selected defects to determine the probability of detection as a function of defect depth and other parameters.

6.0 CONCLUSIONS

1.0 The in-service (CIGAR-type) inspection of CANDEV tube DB3 recorded all the defects detected by the new manufacturing inspection, plus four or five more.

2.0 Three defects – L4, M4 and N4 – were not detected either by CIGAR or by BAL.

3.0 The increased sensitivity of the CIGAR inspection is due to the standard practice of increasing the scanning gain until the fuel bundle scratches are seen ("grass-level plus" scanning).

7.0 ACKNOWLEDGEMENTS

CANDEV tube DB3 was loaned by Mr. W. Mayo, CRNL. The BAL inspection was performed by Mr. R.O. Trowski. Mr. D. W. Donnelly assisted with the CIGAR inspection. The work was funded by Design and Development.

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1. See, for example, AECL Technical Specification TS-xx-31110-5, prepared by S. Venkatapathi, June 8, 1978.

2. S.M. Kramer and M.P. Dolbey, OHRD Report No. M86-118-K, October 31, 1986.

3. M.D.C. Moles, OHRD Report No. 85-170-K, July 10, 1985.

4. M.D.C. Moles, OHRD Report No. 85-316-K, November 7, 1985.

5. M.P. Dolbey and A.L. Allen, OHRD Report No. M86-66-K, June 19, 1986.

6. Memo from S.M. Kramer to G.J. Field, March 24, 1987, file no. 83.136(T).

TABLE 1

Comparison of Old Manufacturing Inspection (CRNL), New Manufacturing Inspection (BAL) and In-Service Inspection on DB3 (OHRD-CIGAR)

	Old Manufacturing Inspection	New Manufacturing Inspection	In-Service Inspection
Normal Beam Transducers	15 MHz, spot focussed	100 MHz spot focussed	15 MHz spot focussed
Shear Wave Transducers	5 MHz spot or line-focussed	10 MHz spot focussed	10 MHz spot focussed
Raster Size	Typically 2±0.5 mm, but some variation	1 mm (max)	3 mm or less
Reject Threshold (Shear)	76 micron notch	76 micron notch	Depends on defect characterization
Recording Threshold (Shear)	76 micron notch+	76 micron notch + 12 dB	Power check* plus 20-26 dB
Inspection from	Outside	Outside	Inside

+Reflectors up to 11 dB below this are re-evaluated.
*Similar in amplitude to 76 micron notch.

TABLE 2

Comparison of BAL (New Manufacturing Inspection Procedure) Results with CIGAR (In-Service Inspection) Results for Detection (50% FSH Threshold in Both Cases)

Defect	O.D. Defects BAL	CIGAR	Defect	I.D. Defects BAL	CIGAR
K8	Y	Y	N9	Y	N.S.
K7	Y	Y	N8	Y	Y
K6	Y	Y	N7	Y	Y
K5	Y	Y	N6	Y	Y
K4	Y	Y	N5	Y	Y
K3	Y	Y	N4	X	X
K2	Y	Y	N3	Y	Y
K1	Y	Y	N2	X	?Y
L9	Y	N.S.	N1	X	Y
L8	Y	Y	M8	Y	Y
L7	X	Y	M7	Y	Y
L6	Y	Y	M6	Y	Y
L5	X	N.S.	M5	Y	Y
L4	X	X	M4	Y[1]	X
L3	Y	Y	M3	X	Y
L2	Y	Y	M2	X	Y
L1	Y	N.S.	M1	X	Y

Y = Recorded

X = Not Recorded

[1]Probably M3

N.S. = Not Scanned

TABLE 3

Comparison of Signal Amplitudes from Inside Surface Defects

ID	Defect	BAL % FSH	OHRD % FSH
	N9	> 100	N.S.
	M8	> 100	> 100
	N8	> 100	> 100
	M7	> 100	> 100
	N7	> 100	> 100
	M6	> 100	> 100
	N6	98	> 100
	M5	> 100	> 100
	N5	> 100	> 100
	M4	0	0
	N4	0	0
	M3*	> 100	> 100
	N3	50	> 100 (single pass)
	M2	> 40+	> 100 (on single pass)
	N2	> 40+	?100**
	M1	> 40+	> 100 (on single pass)
	N1	> 40+	> 100

*Labelled M4 in BAL output.

+There are a number of small reflectors > 40% over the appropriate region, but these are difficult to relate to any particular defect on the BAL charts.

**Defect identification not confirmed.

TABLE 4

Comparison of Signal Amplitudes From Outside Surface Defects

OD	Defect	BAL % FSH	OHRD % FSH
	L9	> 100	N.S.
	K8	> 100	> 100%
	L8	> 100	> 100
	K7	> 100	> 100
	L7	30	> 100
	K6	> 100	> 100
	L6	> 100	> 100
	K5	> 100	> 100
	L5	35	N.S.
	K4	95	> 100
	L4	0	0
	K3	>100	> 100
	L3	55	> 100
	K2	> 100	> 100
	L2	> 100	> 100
	K1	> 100	> 100
	L1	50	N.S.

N.S. = Not Scanned.

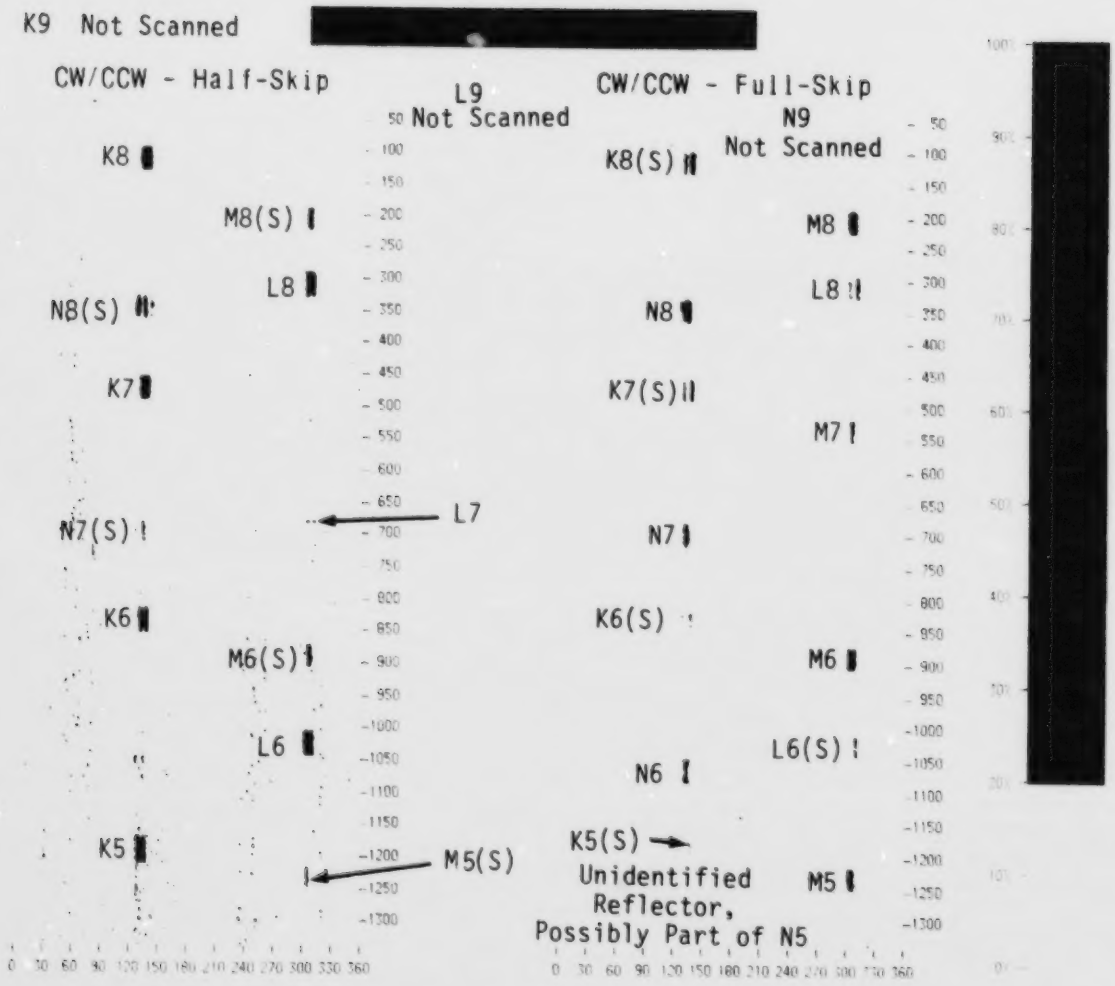

FIGURE 1

C-SCAN OF DB3 SECTION CONTAINING DEFECTS K,L,M,N 5-8
AT TYPICAL CIGAR LEVELS

(NOTE: HALF SKIP REFERS TO OUTSIDE SURFACE,
FULL SKIP REFERS TO INSIDE SURFACE)

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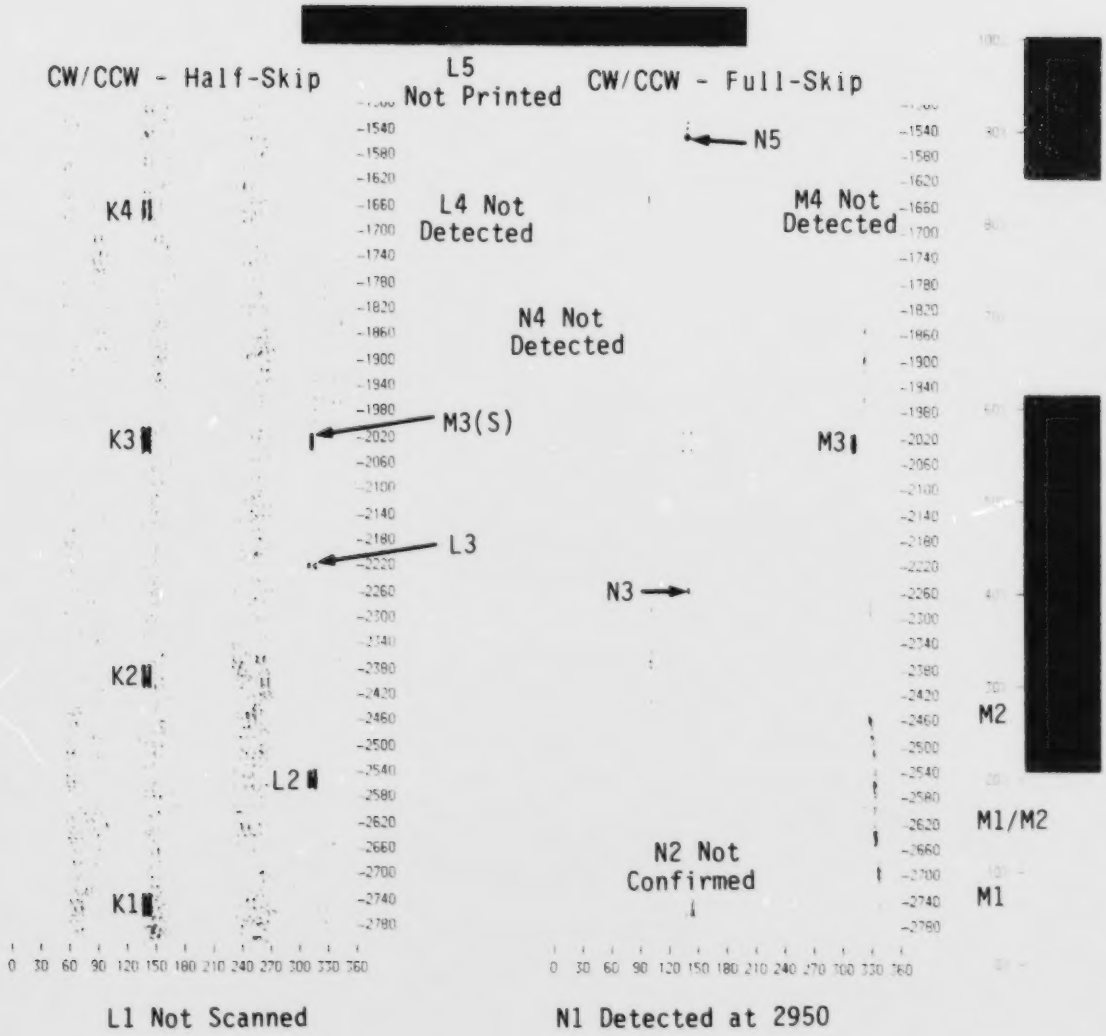


FIGURE 2

C-SCAN OF DB3 SECTION CONTAINING DEFECTS
K,L,M,N 1-4 AT TYPICAL CIGAR LEVELS

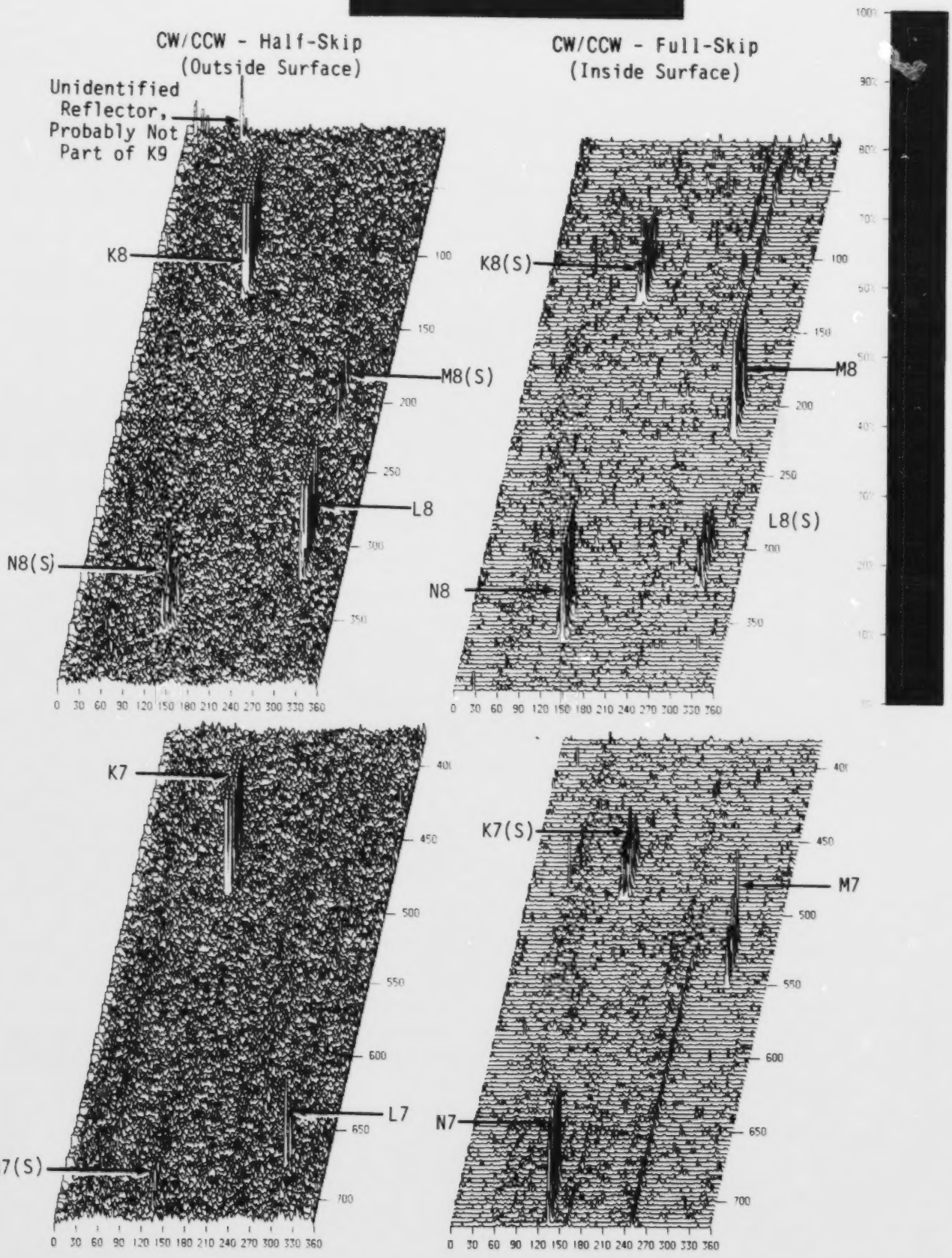


FIGURE 3a
ISOMETRIC PRINT-OUTS OF LENGTH 14 - 720 mm

176458-RD

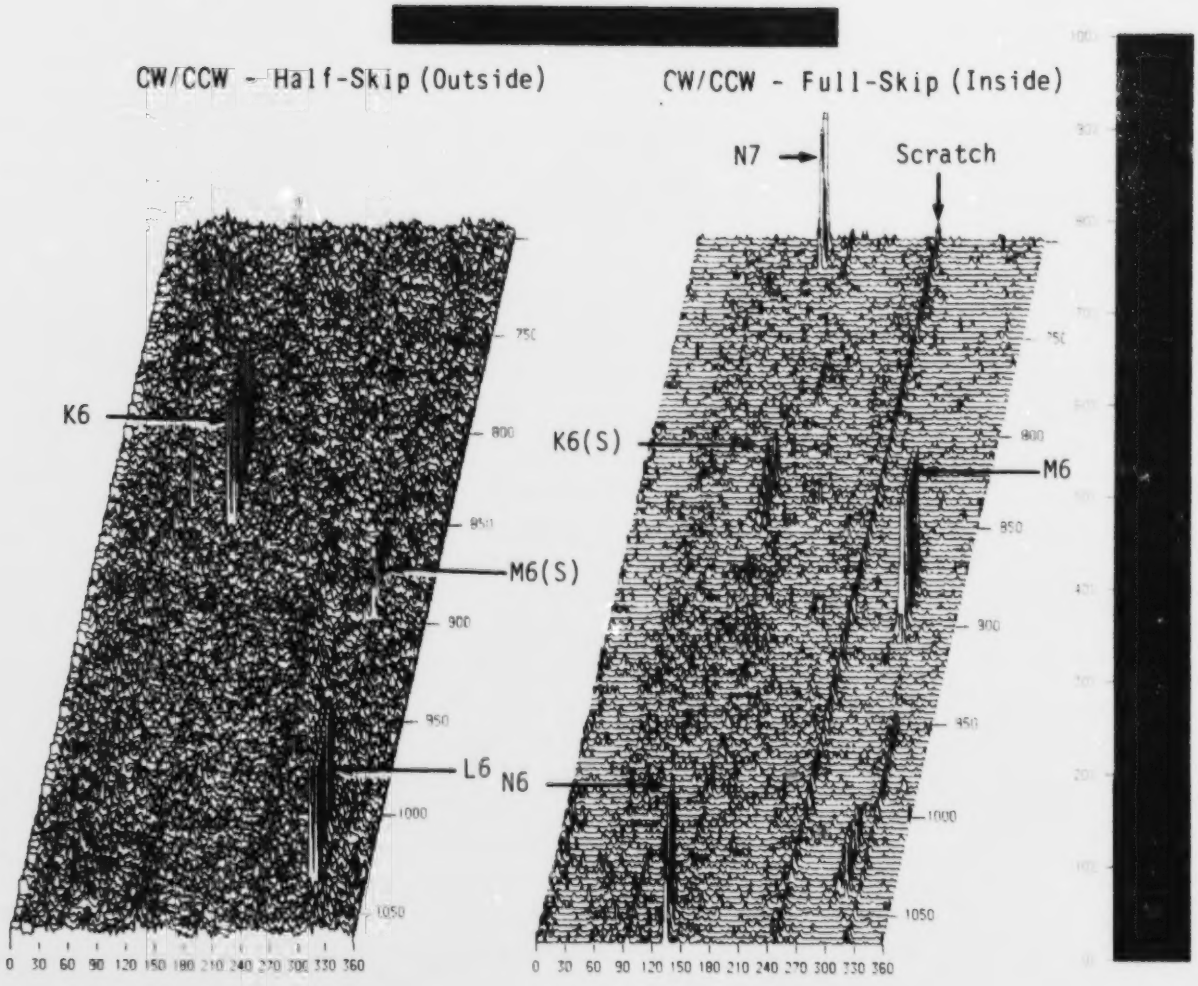


FIGURE 3b
ISOMETRIC PRINT-OUTS OF LENGTH 700 - 1065 mm

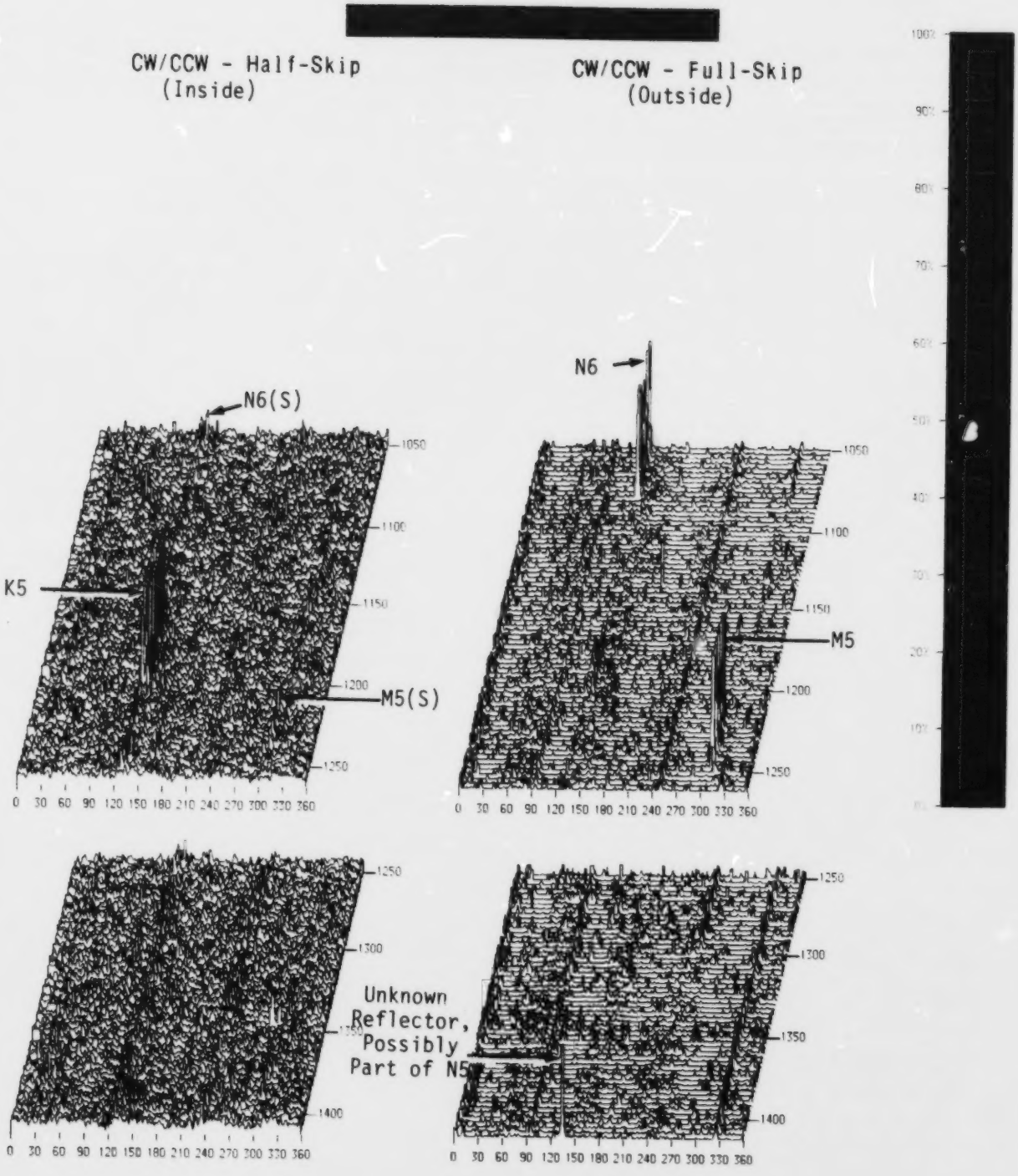


FIGURE 3c
ISOMETRIC PRINT-OUTS OF LENGTH 1040 - 1412

[redacted]

CW/CCW - Half-Skip
(Outside)

CW/CCW - Full-Skip
(Inside)

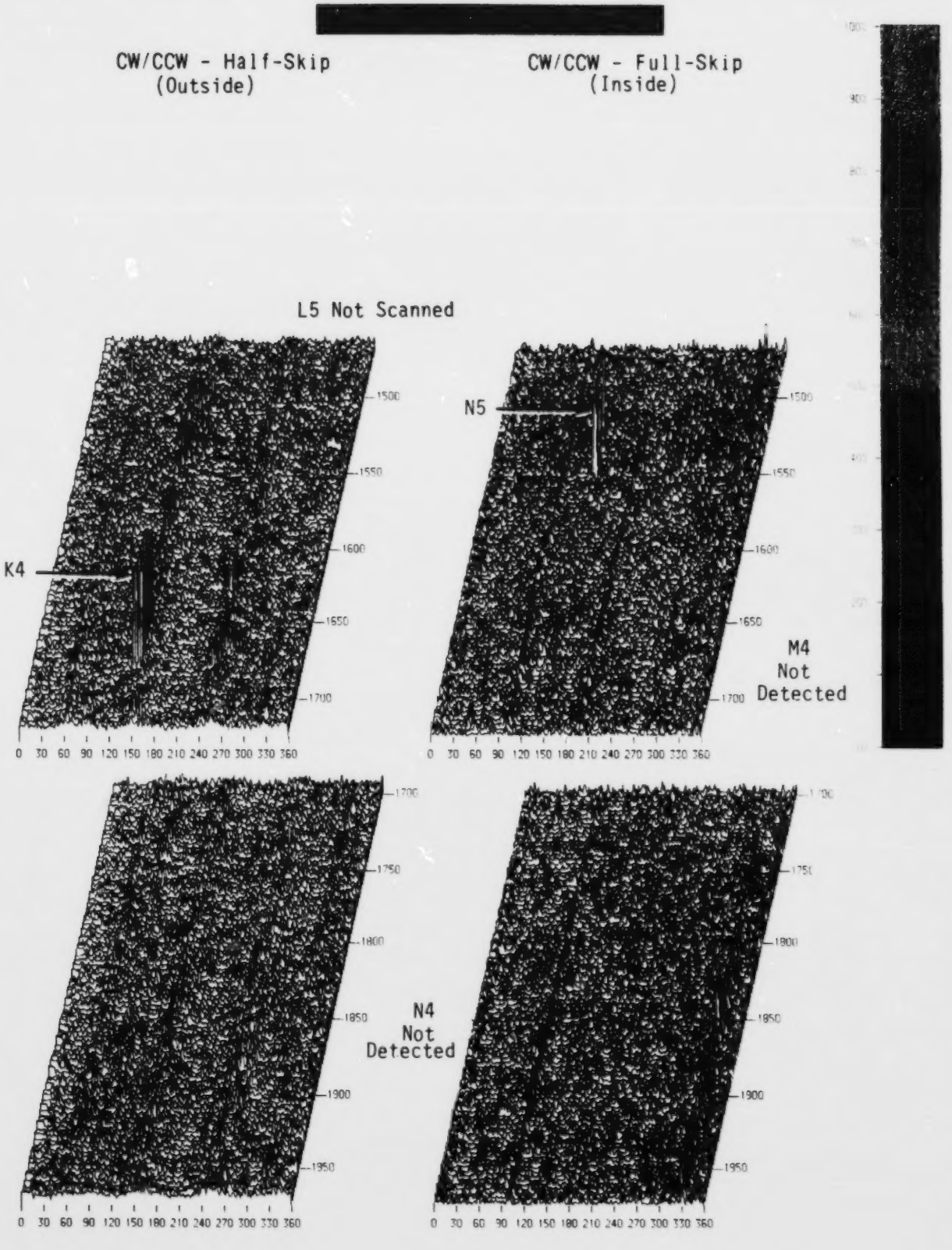


FIGURE 3d

ISOMETRIC PRINT-OUTS OF LENGTH 1460 - 1970.

(NOTE: REGION FROM 1412 - 1460 WAS NOT SCANNED).

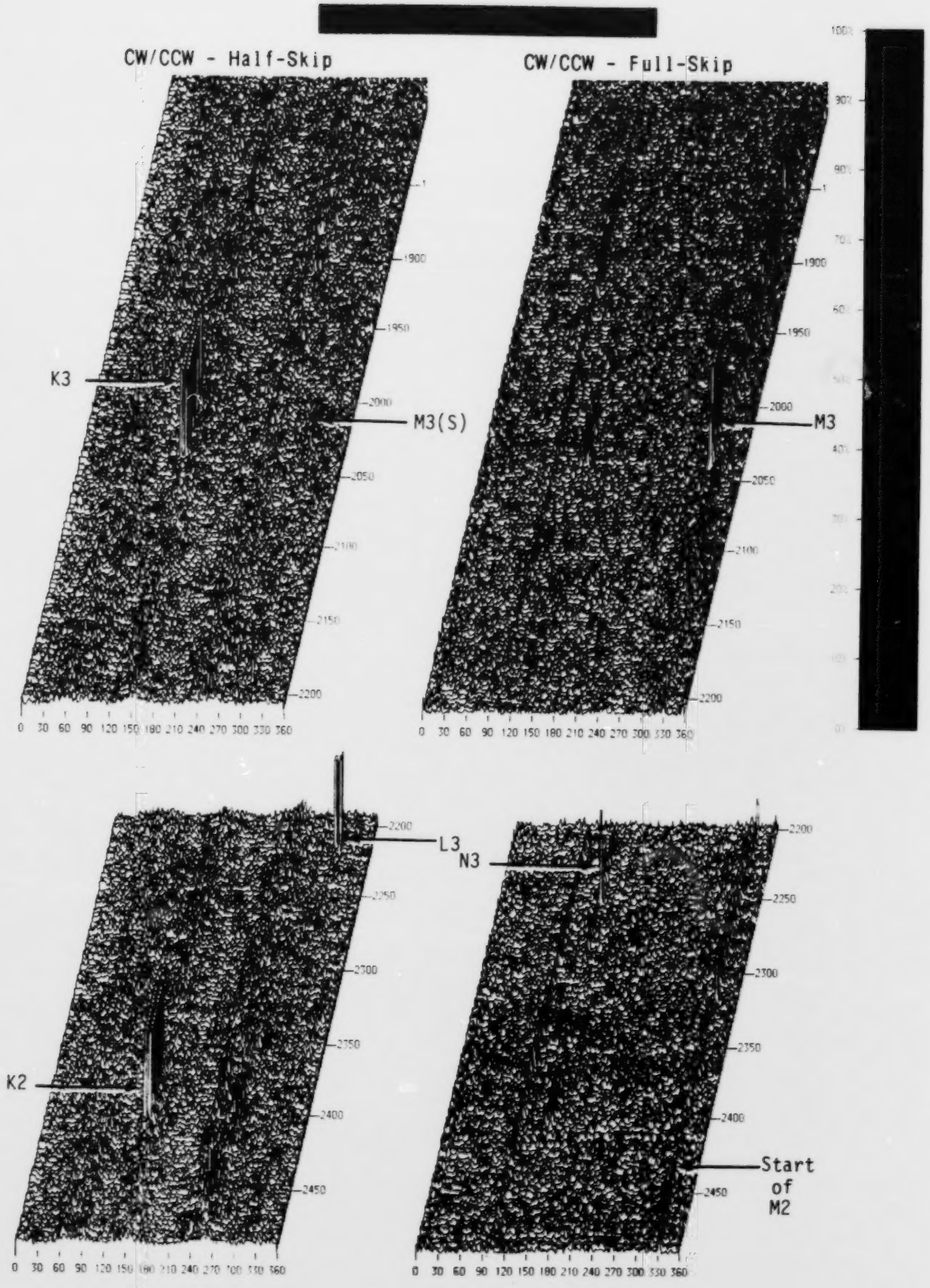


FIGURE 3e
ISOMETRIC PRINT-OUTS OF LENGTH 1800 - 2490

176462-RD

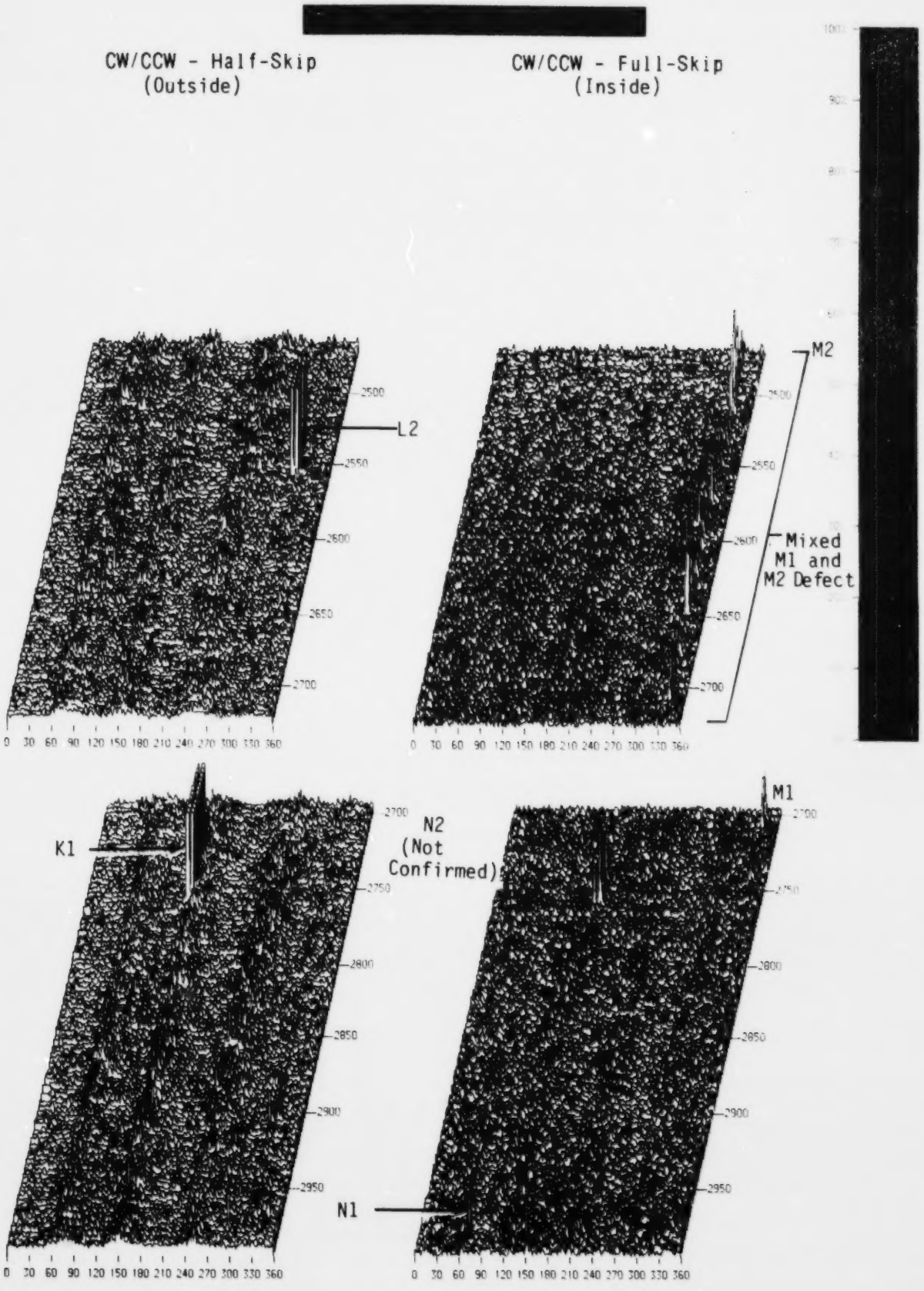


FIGURE 3f
ISOMETRIC PRINT-OUTS OF LENGTH 2460 - 2990

176463-RD

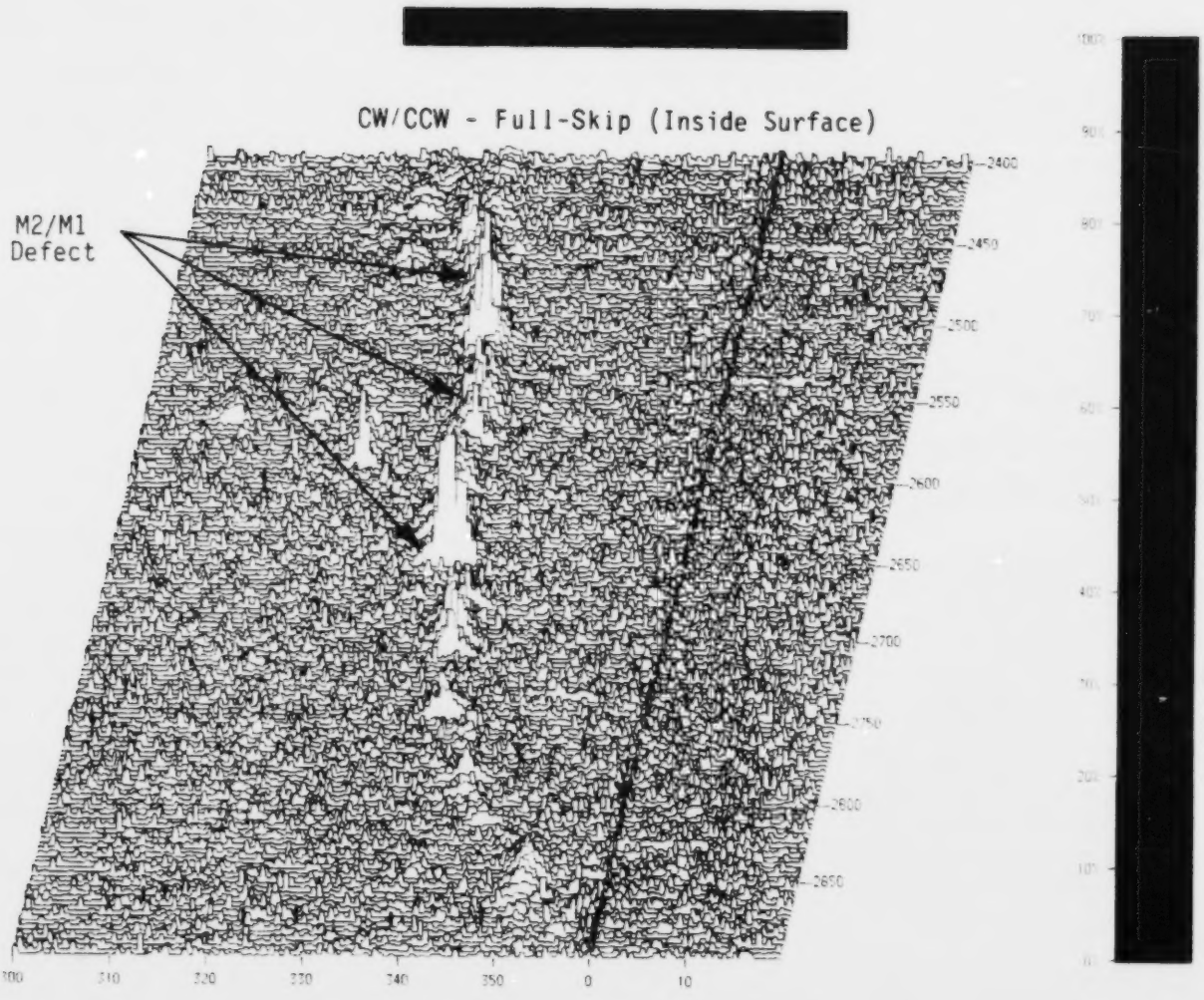
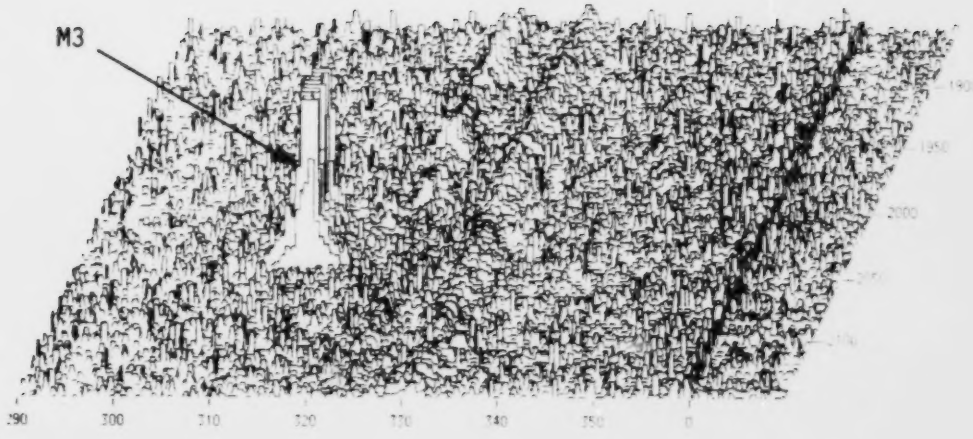


FIGURE 4
"DETAILED SCAN" OF M1/M2 DEFECT

176464-RD

[redacted]

CW/CCW - Full-Skip (Inside Surface)



[redacted]

FIGURE 5
"DETAILED SCAN" OF M3 DEFECT

176465-RD

[redacted]

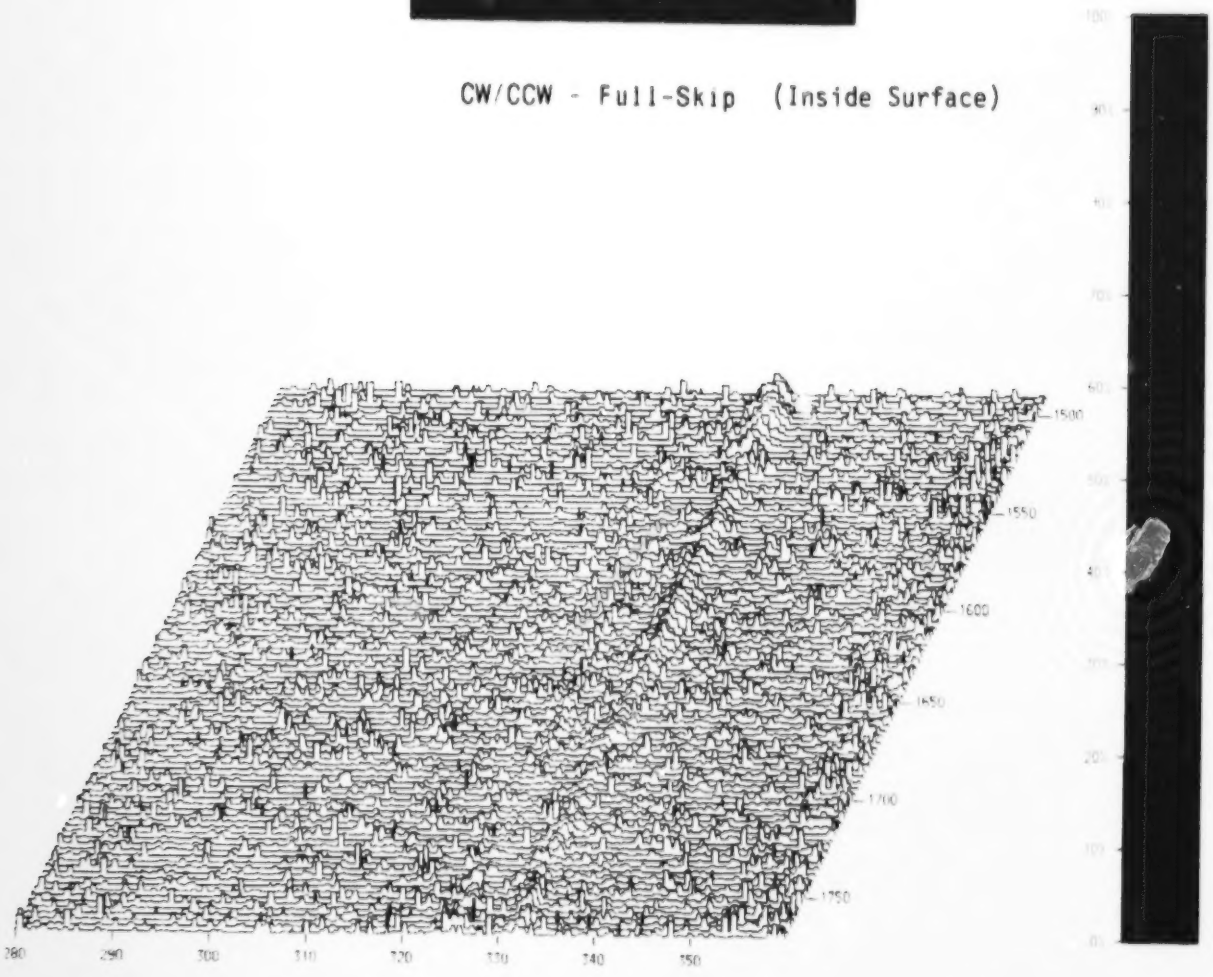


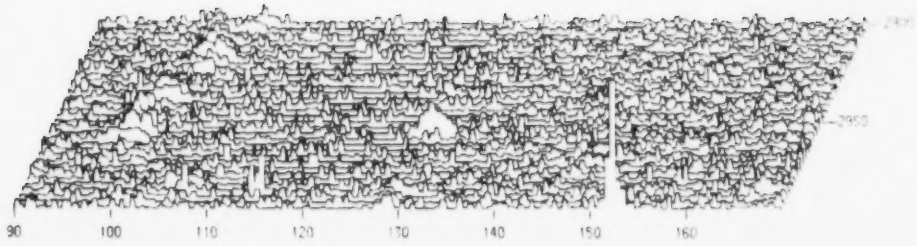
FIGURE 6
"DETAILED SCAN" OF AREA CONTAINING DEFECT M4.
NO DEFECT REPORTABLE

176466-RD

[redacted]

CW/CCW - Full-Skip (Inside Surface)

[redacted]



N1

FIGURE 7
"DETAILED SCAN" OF START OF N1 DEFECT

[redacted]

CW/CCW - Full-Skip (Inside Surface)

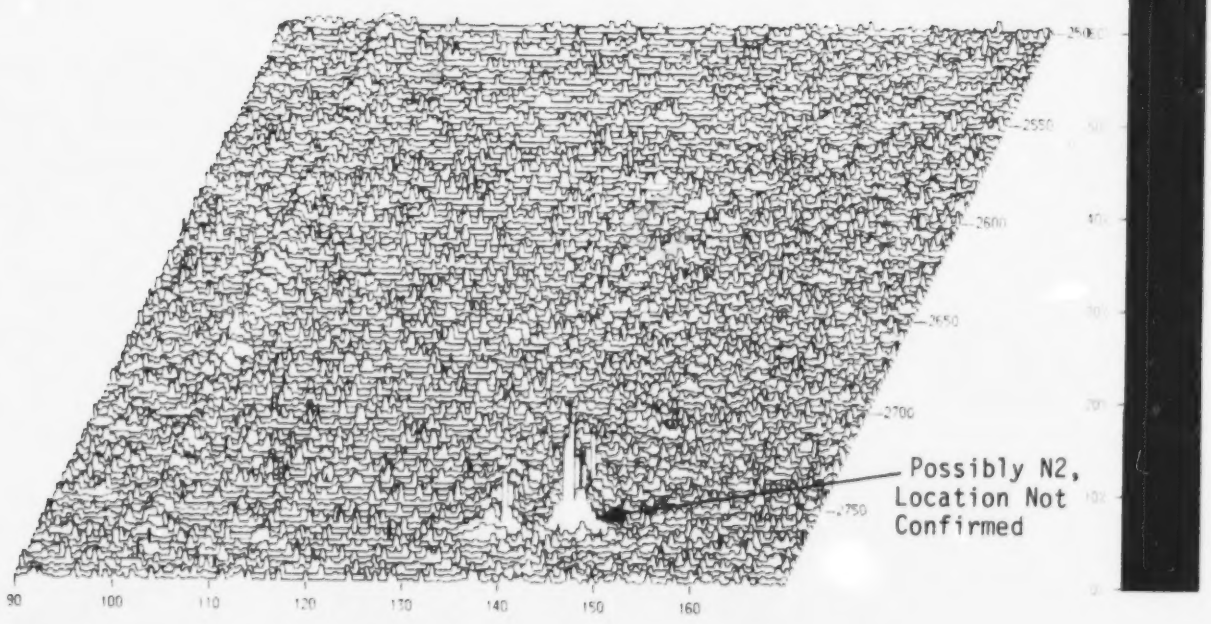


FIGURE 8

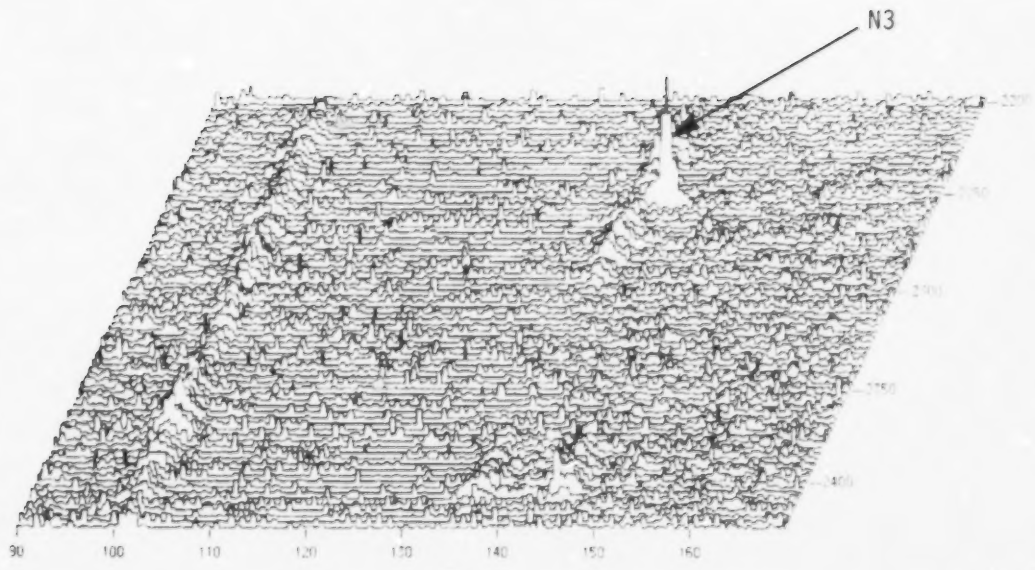
"DETAILED SCAN" OF N2 DEFECT REGION,
SHOWING POSSIBLE N2 DEFECT.

NOTE THAT THIS DID NOT QUITE CORRELATE
WITH MEASURED LOCATION

176468-RD

[redacted]

CW/CCW - Full-Skip (Inside Surface)



[redacted]

FIGURE 9

"DETAILED SCAN" OF N3 DEFECT

176469-RD

[redacted]

CW/CCW - Full-Skip (Inside Surface)

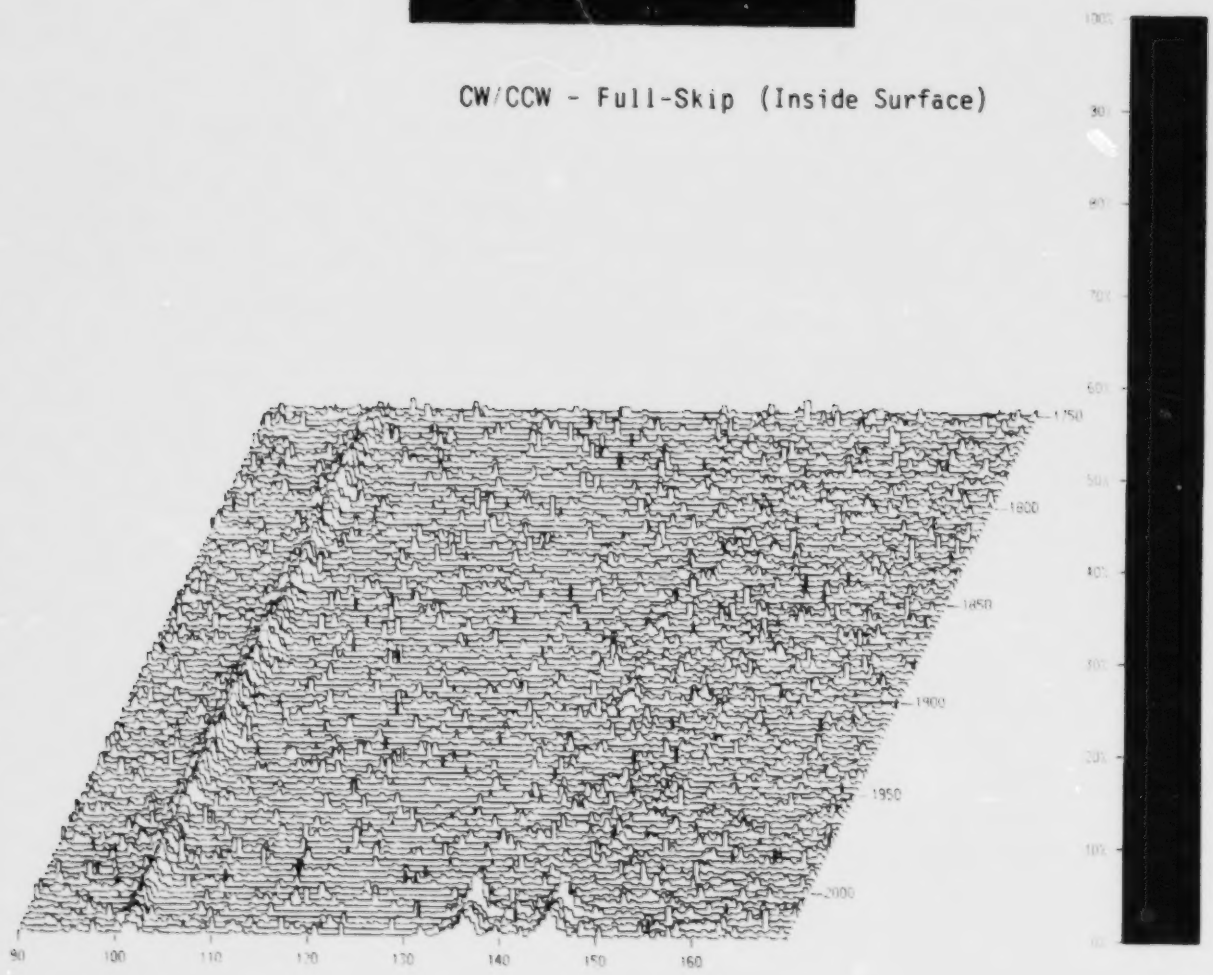


FIGURE 10

"DETAILED SCAN" OF AREA CONTAINING N4 DEFECT

176470-RD

[redacted]

CW/CCW - Half-Skip (Outside Surface)

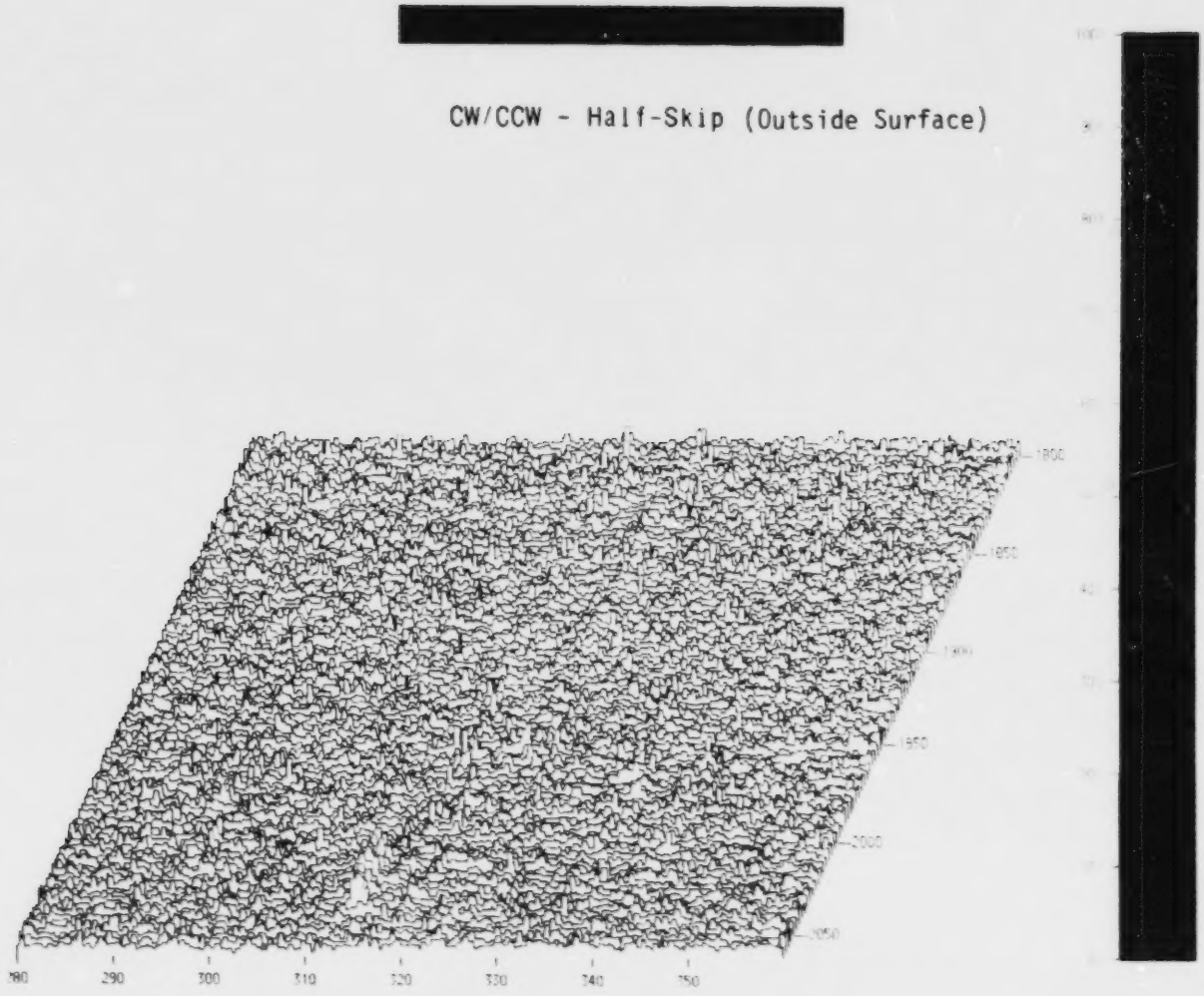


FIGURE 11
"DETAILED SCAN" OF L4 DEFECT AREA

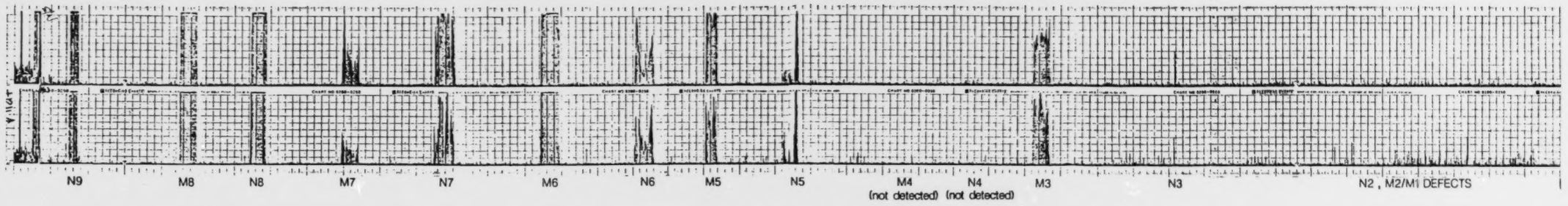


FIGURE 12

BAL NEW MANUFACTURING INSPECTION
STRIP CHART RECORDINGS ON DB3
INSIDE SURFACE PLOTS FOR TWO
CIRCUMFERENTIAL PROBES USING
76 MICRON NOTCH + 12 dB

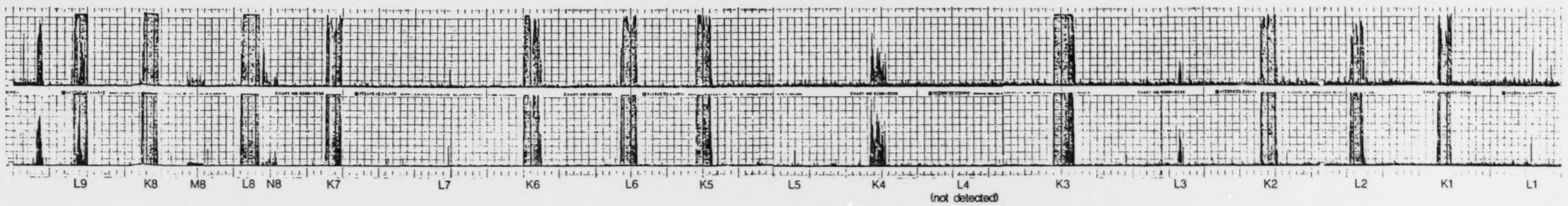


FIGURE 13

BAL NEW MANUFACTURING INSPECTION
STRIP CHART RECORDINGS ON DB3
OUTSIDE SURFACE PLOTS FOR TWO
CIRCUMFERENTIAL PROBES USING
76 MICRON NOTCH + 12 dB